# Paleomagnetism in the Hazara-Kashmir Syntaxis, NE Pakistan

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# Paleomagnetism in the Hazara-Kashmir Syntaxis, NE Pakistan

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## ABSTRACT

Three sections well exposed throughout a 6–8 km thick pile of molassic red beds (Murree formation) have been studied in the Subhimalayan tectonic unit of the Hazara-Kashmir Syntaxis. Paleomagnetic studies have revealed stable directions of natural remanent magnetization (NRM). Thermal demagnetization experiments suggest that detrital haematite with high unblocking temperatures carries the characteristic remanence directions.

In the southernmost section, the Jhelum valley, the weakly tectonized Murree beds are characterized by flattened AMS ellipsoids resulting from diagenetic compaction. The *inclination values* of the dip corrected primary directions suggest that the Murree foreland basin started to develop at about 8° N during the early suturing of India and the development of island arcs to the north. Micropaleontological age determinations of the lower most Murree sediments have indicated Late Paleocene deposition (55 my); India has moved northward by at least 2600 km since collision in the Paleocene. The *declination values* of the dip corrected primary directions suggest clockwise rotation relative to the Indian craton by about 45° of the block supporting the Murree formation. A rotation model which is consistent with the transport direction pattern around the Syntaxis and the rotation of thrust sheets derived by NRM-dat is proposed. This model symply relates the convergent transport directions with the mean indentation directions of India into Asia.

Towards the northern two sections, in the Neelum – and Kaghan valleys, quantitative strain mapping shows a progressive increase of deformation. The characteristic NRM directions tend to rotate passively towards the cleavage plane and the AMS ellipsoids show a clear magnetic foliation parallel to the cleavage planes. Both the NRM directions and the AMS ellipsoids reflect the increasing strain from south to north.

## ZUSAMMENFASSUNG

Durch den Kern der Hazara-Kashmir Syntaxis, welcher von 6–8 km mächtigen roten Molasse-Sedimenten des Subhimalayas eingenommen wird (Murree Formation), wurden drei gut aufgeschlossene Profile studiert. Paläomagnetische Messungen an Feldproben haben stabile Richtungen der natürlichen remanenten Magnetisierung (NRM) ergeben, wobei thermische Entmagnetisierungsexperimente auf Hämatit als Träger der Remanenz hinweisen.

Im Jhelum Tal (südlichstes Profil) sind die tektonisch sehr schwach deformierten Murree Sedimente durch geplättete AMS-Ellipsoide in der Schichtungsebene charakterisiert, was durch diagenetische Kompaktion erklärt werden kann. Die *Inklinationswerte* der primären NRM-Richtungen deuten auf die Bildung des Molasse-Vorlandbekkens auf einer nördlichen Breite von ca. 8° hin. Die ältesten Murree Sedimente sind mit einem Alter von spätem Paläozän (55my) belegt. Demgemäss ist der Indische Kraton seit seiner Kollision mit dem Inselbogen mindestens 2600 km nach Norden gewandert. Die *Deklinationswerte* der NRM-Richtungen weisen auf eine Uhrzeigersinn Rotation der Murree-Formation relativ zum Indischen Kraton hin. Es wird ein Rotationsmodell vorgeschlagen, das so-

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wohl den Decken-Transportrichtungen im Raume der Hazara-Kashmir Syntaxis –, als auch den paläomagnetischen Bewegungen (Blockrotation der Murree Formation, Konvergenzrichtung Indischer Kraton) gerecht wird.

Im Neelum- und Kaghan Tal (mittleres und nördliches Profil) hat die Kartierung von Deformationsstrukturen eine systematische Zunahme der endlichen Verformung gegen Norden hin ergeben. Die charakteristischen NRM-Richtungen rotieren passiv in die Schieferungsebene und die AMS-Daten widerspiegeln eine klare magnetische Foliation parallel zur Schieferung. Diese Zunahme der tektonischen Verformung von Süd nach Nord ist aus NRM-Richtungen und AMS-Ellipsoiden ableitbar.

## 1. Geological setting

The Hazara-Kashmir Syntaxis consists of a series of overlapping thrust sheets. They are made up of various Precambrian, Paleozoic and Mesozoic formations which have been overthrust on Tertiary molasse deposits, known as Murree formation. Two major thrusts can be distinguished, a higher Panjal thrust and a lower Murree thrust (Fig. 1). The Murree thrust corresponds to the Main Boundary thrust (MBT) in India. Both thrusts show bowed strike trends as a result of folding in the syntaxial bend. Along the eastern border of the Syntaxis the Murree and Panjal thrust planes dip 50°–70° towards NE, along the apex 50°–70° towards N. Along the western border of the Syntaxis the thrusts become steeper and merge together in one subvertical thrust between Balakot and Muzzaffarabad.

The main lithotypes forming the *Subhimalayan tectonic unit,* or core of the Syntaxis, are the sandstones and shales of the Murree formation. The characteristic feature of these somewhat monotonous, upwards fining, continental to shallow marine (tidal flat) clastic series is a pervasive cyclicity interpreted as developing in an environment of meandering tidal channels in a continuously subsiding foreland basin. Age determinations based on syndepositional nummulites and assilines indicate a late Paleocene to early-middle Eocene age for the Murree formation (Bossart & Ottiger 1989). The structure of this region is dominated by a large anticlinal structure, the Muzaffarabad anticline whose core consists of Paleocene deposits and of the Late Precambrian to Cambrian Abbottabad formation. Metamorphism reaches prehnite-pumpellyite facies in this Subhimalayan tectonic unit.

The Murree thrust separates the Subhimalaya from the lower elements of the Lesser Himalaya, known as the Panjal imbricate zone. This zone includes different imbricate slices that consist of Carboniferous to Permian tilloides at the base, followed by dark green to olive colored schists of basic to intermediate composition, the Panjal volcanics, and crinoidal- and gastropod-bearing Triassic limestones and dolomites at the top.

The higher tectonic element of the Lesser Himalaya is lying above the Panjal thrust and consists of Precambrian rocks, called the Salkhala unit. It is exposed in the north

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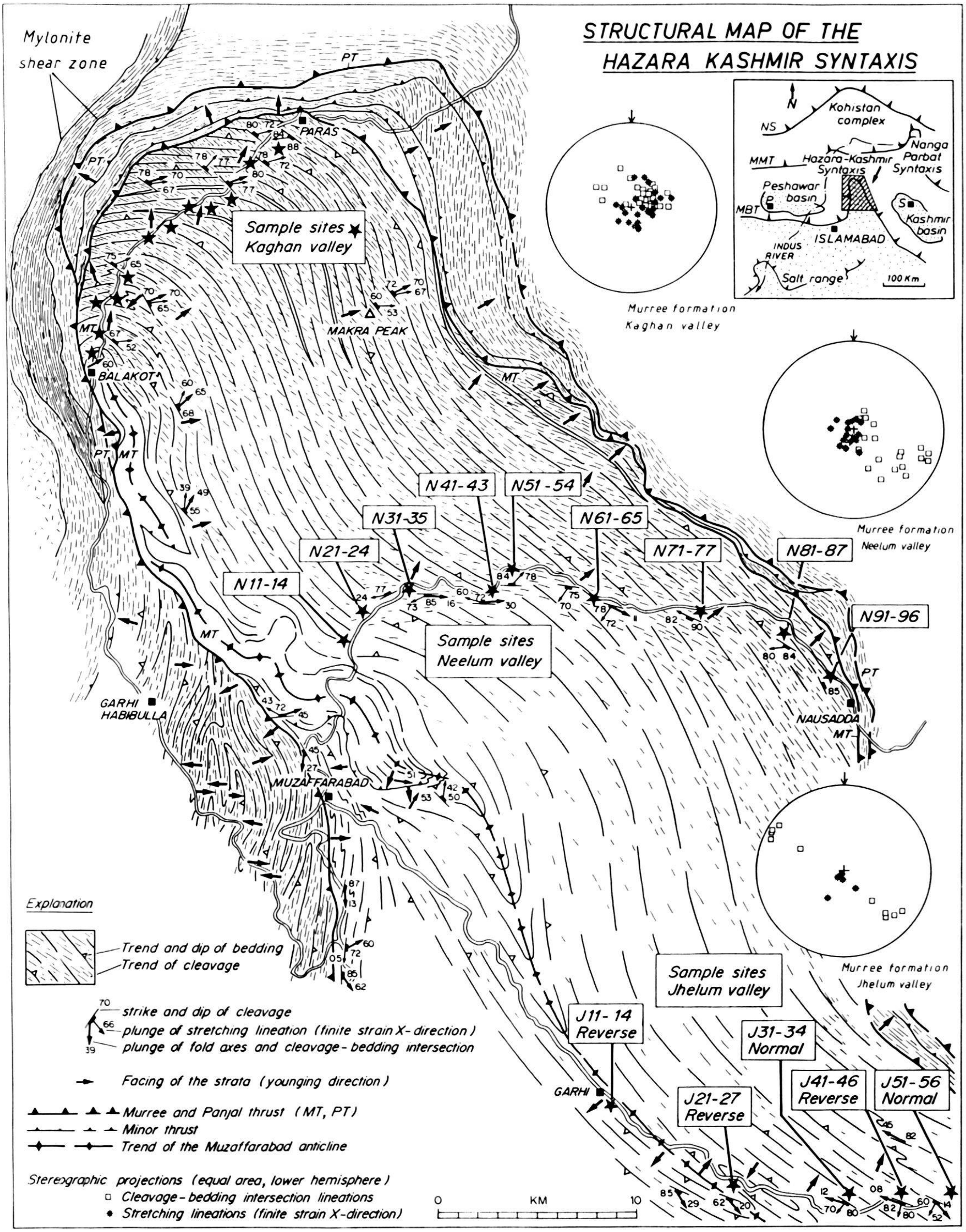
Fig. 1. Samples sites of the Jhelum (J)-, Neelum (N)- and Kaghan sections. In the Jhelum- (J) and Neelum (N) sections the sites are numbered from west to east. The first digit of the two digit numbers indicates the site whereas the second digit denotes the sample number. Three tectonic units are distinguished (Greco et al. 1989): a Subhimalayan unit (Murree formation) in the footwall of the Murree thrust, a Lesser Himalayan unit (including all elements between the mylonite shear zone and the Murree thrust) and a Higher Himalayan tectonic unit W and N of the mylonite zone. Structural map based on field and survey mapping by P. Bossart, D. Dietrich, A. Greco, R. Ottiger & J. Ramsay.


STRUCTURAL MAP OF THE
HAZARA KASHMIR SYNTAXIS
Mylonite
shear zone
PT
MT
PARAS
Sample sites
Kaghan valley
MAKRA PEAK
BALAKOT
N41-43
N51-54
N31-35
N61-65
N21-24
N71-77
N81-87
N11-14
N91-96
Sample sites
Neelum valley
GARHI
HABIBULLA
NAUSADDA
MUZAFFARABAD
Kohistan
complex
NS
MMT
Hazara-Kashmir
Syntaxis
Nanga
Parbat
Syntaxis
Peshawar
basin
MBT
ISLAMABAD
Kashmir
basin
INDUS
RIVER
Salt range
100 Km
Murree formation
Kaghan valley
Murree formation
Neelum valley
Murree formation
Jhelum valley
Sample sites
Jhelum valley
J11-14
Reverse
J31-34
Normal
J41-46
Reverse
J51-56
Normal
J21-27
Reverse
GARHI
Explanation
Trend and dip of bedding
Trend of cleavage
strike and dip of cleavage
plunge of stretching lineation (finite strain X-direction)
plunge of fold axes and cleavage-bedding intersection
Facing of the strata (younging direction)
Murree and Panjal thrust (MT, PT)
Minor thrust
Trend of the Muzaffarabad anticline
Stereographic projections (equal area, lower hemisphere)
Cleavage-bedding intersection lineations
Stretching lineations (finite strain X-direction)
0 KM 10

and northeastern part of the Syntaxis and consists of various crystalline rocks, which have undergone upper greenschist grade metamorphism (Greco et al. 1989) during the last main Himalayan deformation (i.e. the thrusting phase). In the hangingwall of this Salkhala unit there is a 1–5 km wide mylonite shear zone; it becomes very distinct west and northwest of Balakot (Fig. 1). We deduce a Neogene age for this deformation, because the mylonites affect the Mesozoic rocks of the Panjal imbricate zone, and also cut the regional Himalayan cleavage. The sense of shear can be determined easily from porphyroclast geometry in granitic mylonites as well as with the geometry of shear bands in micaceous mylonites: the shear direction is almost parallel to the stretching lineation and the sense is consistently sinistral relative to the map pattern. The western part of the Syntaxis has been displaced towards the south some tens of kilometers relative to the eastern part. Greco et al. (1989) have shown, that this mylonite shear zone separates the tectonic units of the Lesser- and the Higher Himalaya and is therefore related to the Main Central thrust (MTC). The Cambrian Mansehra Granite (Le Fort 1980), which is found in the hanging wall of this mylonite zone, is now related to the Higher Himalayan tectonic unit.

### *1.1 The tectonic structures in the Subhimalayan Murree formation* (Fig. 1)

Many structures are observable in the Murree formation: bedding with a well defined younging direction, slaty cleavage, cleavage-bedding intersection and extension lineations (X-axes). The bedding- and cleavage-strikes generally trend in a northwestward direction (cleavage plunge steeper than the one of bedding). From S to N as well as across the Syntaxis, the cleavage increases in intensity. Fibrous vein systems have developed synchronously with the formation of the cleavage and are particularly well developed in the north, where finite strains, measured on reduction spots, reach maximum values. Bedding and cleavage are cut discordantly by the Murree thrust. The Muzaffarabad anticline has a fold axis plunging steeply towards NE near Balakot (Kaghan valley), whereas the fold axis plunges at a lower angle towards E or SE near Muzaffarabad (Neelum valley).

The structural map (Fig. 1) is best interpreted with a dome model (Bossart et al. 1988). The two limbs of the domal fold are characterised by a change in the bedding-cleavage relationship: in the Kaghan section, the bedding-cleavage intersection lineations (=fold axes) dip steeply to NE, N and NW, whereas in the Neelum section, these intersections lineations dip with intermediate angles to SE (see stereograms of Fig. 1). The domal crest is defined between these two limbs where bedding- and cleavage-strikes are parallel; it crosses the Syntaxis in a SW-NE direction. This domal fold in the Murree formation developed by layer compression subperpendicular to a southwestward overthrust direction. Its direction was derived by the orientation of the Muzaffarabad anticline and of the finite cleavage and stretching lineations in the Murree formation (mineral reorientation parallel to the longest axis of deformed reduction spots). The Murree fault cuts down the Murree strata from NE to SW. This out of sequence sole thrust, at least in part, must be later than the early doming, but it became involved in the later doming-up process. The hanging wall material of the Murree formation was most probably eroded and deposited in the Siwalik molasse.

### *1.2 The formation of the Hazara-Kashmir Syntaxis*

Three tectonic phases are responsible for the formation of the Syntaxis. The first Himalayan phase includes the overthrusting of the Precambian units (e.g. Salkhala unit) over the Late Paleozoic-Mesozoic units (Panjal imbricate zone). During this thrust event shear induced compression affected also the Murree realm, deforming the Late Precambrian-Cambrian Abbottabad formation and the Paleocene-Eocene Murree shales into an open fold, the Muzaffarabad anticline. Further compression caused the thrusting (Murree thrust) of the already formed tectonic elements over the Murree formation, first cutting the rising Muzaffarabad anticline, and later leading to the formation and intensification of the dome structure. The timing of the dome development is not completely certain, but a correlation of the dome in the Hazara-Kashmir Syntaxis with the Nanga Parbat Syntaxis, which is an uplift structure, seems likely. A tectonic cooling fission track age near the apex of the Hazara-Kashmir Syntaxis which is dated at 16 my (ZEITLER 1985) suggests an up-doming in the early Miocene. The transport direction of all these events was southwestwards.

Subsequently (second phase) a progressive change of overthrust direction leading to a final southeastwards transport direction developed a sinistral ductile shear zone in the already formed chain. This shear zone is a feature of large tectonic scale, induced by differential movement of crustal blocks; it separates the Lesser Himalaya from the Higher Himalaya (GRECO et al. 1989). The strain arising from a narrowing down of this shear zone during its development led to the production of the mylonites west of Balakot.

The final third phase results in a south-southeastward thrust movement, recorded in the western area of the Syntaxis; this mass transport is responsible for the superimposed folding in the Muzaffarabad area as well as the formation of a crenulation cleavage in the higher thrust units. In conclusion, a counterclockwise rotation of overthrust shear direction from NE-SW to NNW-SSE appears to best accord for the structural and geometric data we have observed and for the formation of the Syntaxis.

## 2. Data acquisition and interpretation of NRM measurements

### *2.1 Evaluation of characteristic magnetization components*

Oriented hand samples were taken for paleomagnetic analysis at the sampling localities indicated and numbered on the structural map of Fig. 1. As a result of an earlier pilot study on the natural remanent magnetization (NRM) of the Murree formation, sampling was concentrated mainly on sandstones, mainly coarse grained sandstones. The NRM of the rock specimens which were drilled from the blocks and sliced into cylinders (height 2.2 cm, diameter 2.54 cm), was measured using a highly sensitive ScT cryogenic magnetometer with a noise level less than $10^{-5}$ A/m (GOREE & FULLER 1976). The NRM intensity averages 1.06 mA/m for the whole collection (N=251 specimens) with mean values of 1.69 mA/m (N=45) in the Jhelum valley, 0.83 m/Am (N=88) in the Neelum valley and 1.06 mA/m (N=118) in the Kaghan profile. A significant change in intensity between the three profiles cannot be recognized.

The NRM stability was tested in a few cases by alternating field (AF) demagnetization, but usually by thermal demagnetization (Fig. 2). In many samples one or two

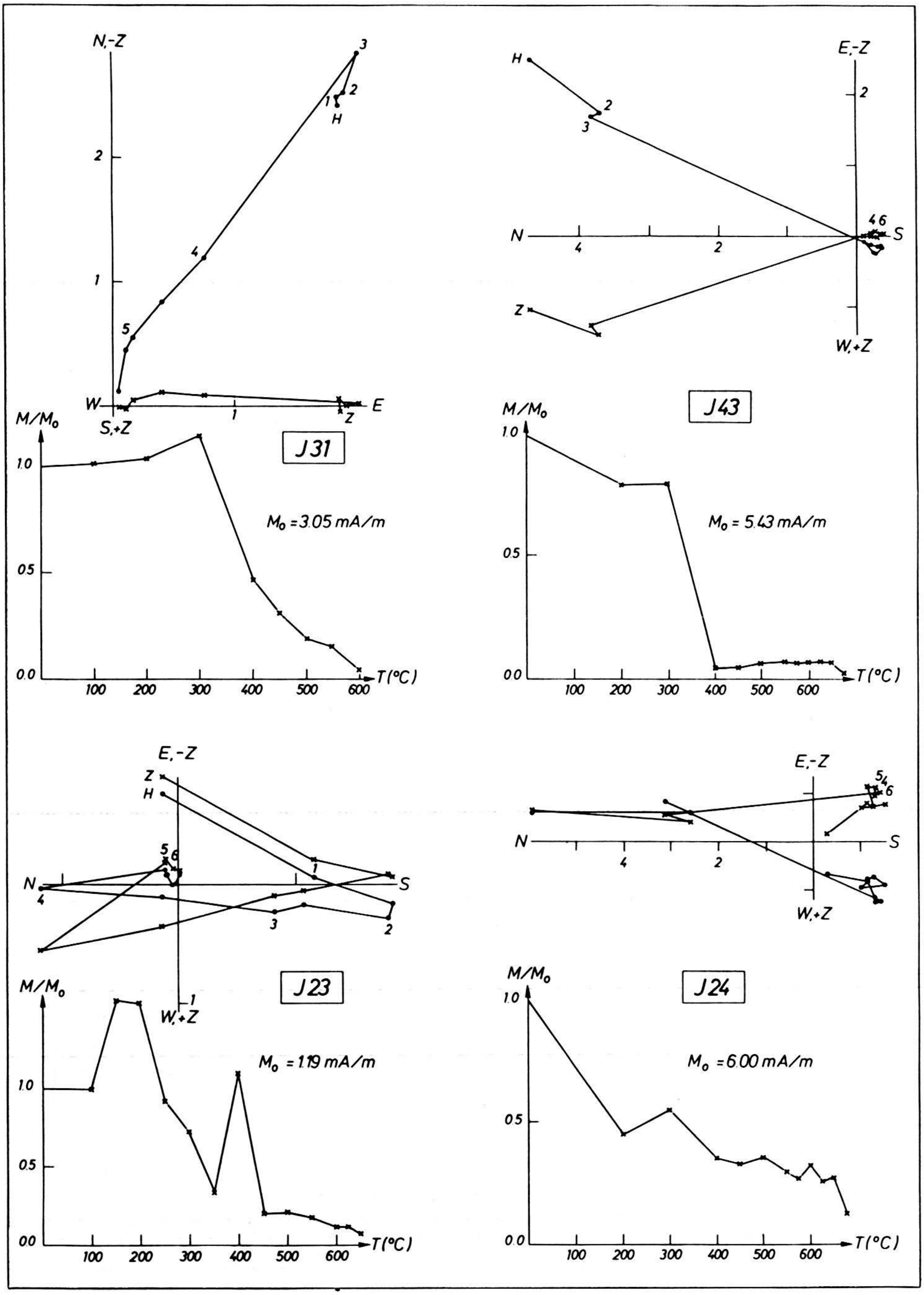



Fig. 2. Thermal demagnetization of natural remanent magnetization (NRM) of representative samples from the Jhelum section (projection of vector components after tectonic dip correction). Numbers along the horizontal component (H) of the orthogonal vector diagrams indicate temperatures in centigrade divided by 100.

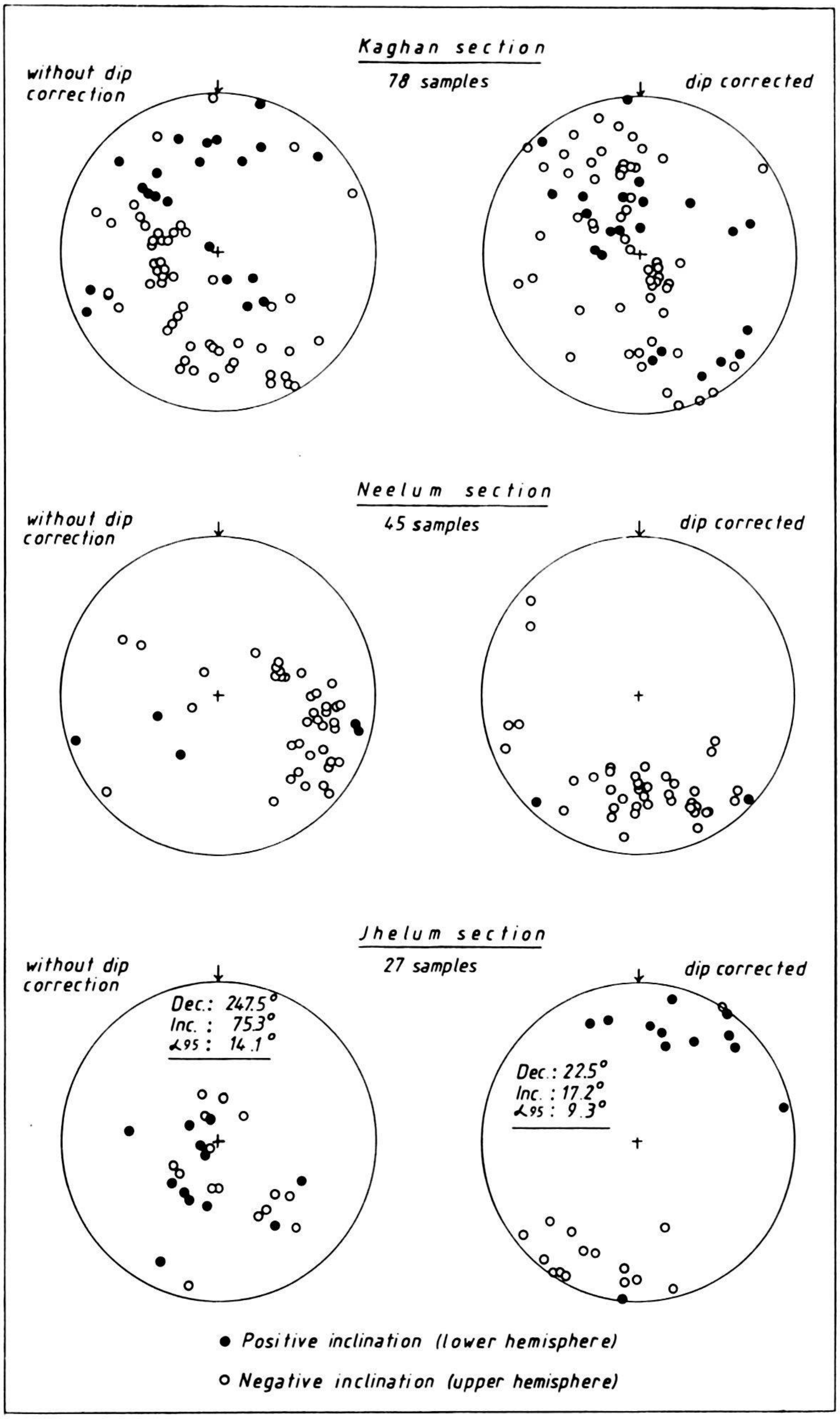



Fig. 3. Characteristic NRM directions of the Jhelum-, Neelum- and Kaghan sections (open circles: upper hemisphere with negative inclinations; filled circles: lower hemisphere with positive inclinations). The left hand side stereograms indicate remanence directions without tectonic dip correction, whereas the right hand side stereograms show remanence directions after tectonic dip correction. Note the increase of scatter of dip-corrected paleomagnetic vectors from the Neelum- to the Kaghan section.

strong secondary NRM components with variable unblocking temperatures (150–400 °C), but also low coercivity (found during AF cleaning, but not demonstrated here) were removed at first. At higher temperatures a NRM component trending towards the origin of projection was often observed which is termed the characteristic remanent magnetization (ChRM) and thought to be of early, if not primary origin. It resides in haematite since the maximum unblocking temperatures exceed 600 °C. Its direction was evaluated using either linear regression analysis after visual inspection of the demagnetization curves or simply stable end point vectors if the vector intensity changed only little during demagnetization. Mineralogical changes at evelated temperatures sometimes prevented clear definition of this component. In the Jhelum valley this primary magnetization was established in 27 of the 45 samples measured. When corrected for tilt of the bedding, it has always a very shallow inclination (Fig. 3) which indicates formation of the sediments at near equatorial position during a depositional or chemical magnetization process. Declinations point mostly NNE or SSW depending on sign of inclination respectively. Polarity changes are indicated throughout the sediment pile. They may be interpreted as evidence for an early magnetization origin. Magnetostratigraphical dating is not possible with the small number of samples. With increasing deformation towards north (Fig. 3: Neelum-, Kaghan-sections) the directional scatter of this high temperature characteristic NRM component also increases.

### *2.2 Inclination of the Jhelum section*

The age of the Murree formation was determined in the Kaghan valley by nummulites and assilines (Bossart & Ottiger 1989). These foraminifera species indicate a earliest age of Paleocene (Ilerdian, 55 my) at the base of the Murree formation and the youngest sample localities show middle Eocene age (Lutetian, about 45 my).

In the southernmost profile practically no internal tectonic deformation (e.g. the formation of a cleavage) is visible. This is also demonstrated by AMS-ellipsoids (Anisotropy of Magnetic Susceptibility; their shapes and orientations after bedding tilt correction reflect sedimentary compaction (Bossart et al. submitted to *Tectonics).*

Continent-continent collision in the western part of the region occurred during deposition of the first Murree red beds. At this time the initiating Murree foreland basin was still in more southern latitudes: the dip corrected characteristic directions (by rotation around the strike direction through the angle of dip) of the Murree formation in the Jhelum valley give a mean inclination of 17.2° (Fig. 3). This indicates, that the paleolatitude of the Murree deposition site was initially (~50 my) located at about 8° N. The original deposition locus was closer to the northwestern border of the Indian craton than its corresponding distance may be today because the cover-block supporting the Murree formation was detached from the basement in the early-middle Miocene. The difference between paleolatitude and present day latitude indicates that the Murree beds have been transported on the Indian craton at least 2600 km to the north. Several workers have proved that there was a sudden decrease in the "rapid northward flight" of India between 60– and 40 my (e.g. Besse et al. 1984, Patriat & Achache 1984). There are not enough accurate inclination data in the Jhelum section to demonstrate this speed decrease, which is clearly shown by the magnetic anomalies in the Indian Ocean (e.g. Powell 1979).

*2.3 Declination of the Jhelum section*

The mean declination of the dip-corrected characteristic directions of 22.5° (±9.7°) in the Jhelum valley indicates a clockwise rotation of the block underlying the Murree Formation since the time of deposition (Fig. 3). A mean value of 50 my has been taken from the age determinations for the Murree formation in the apex area. To calculate the amount of rotation for the Murree beds relative to the stable Indian craton, the counterclockwise rotation of India since 50 my, according to the Apparent Polar Wan-

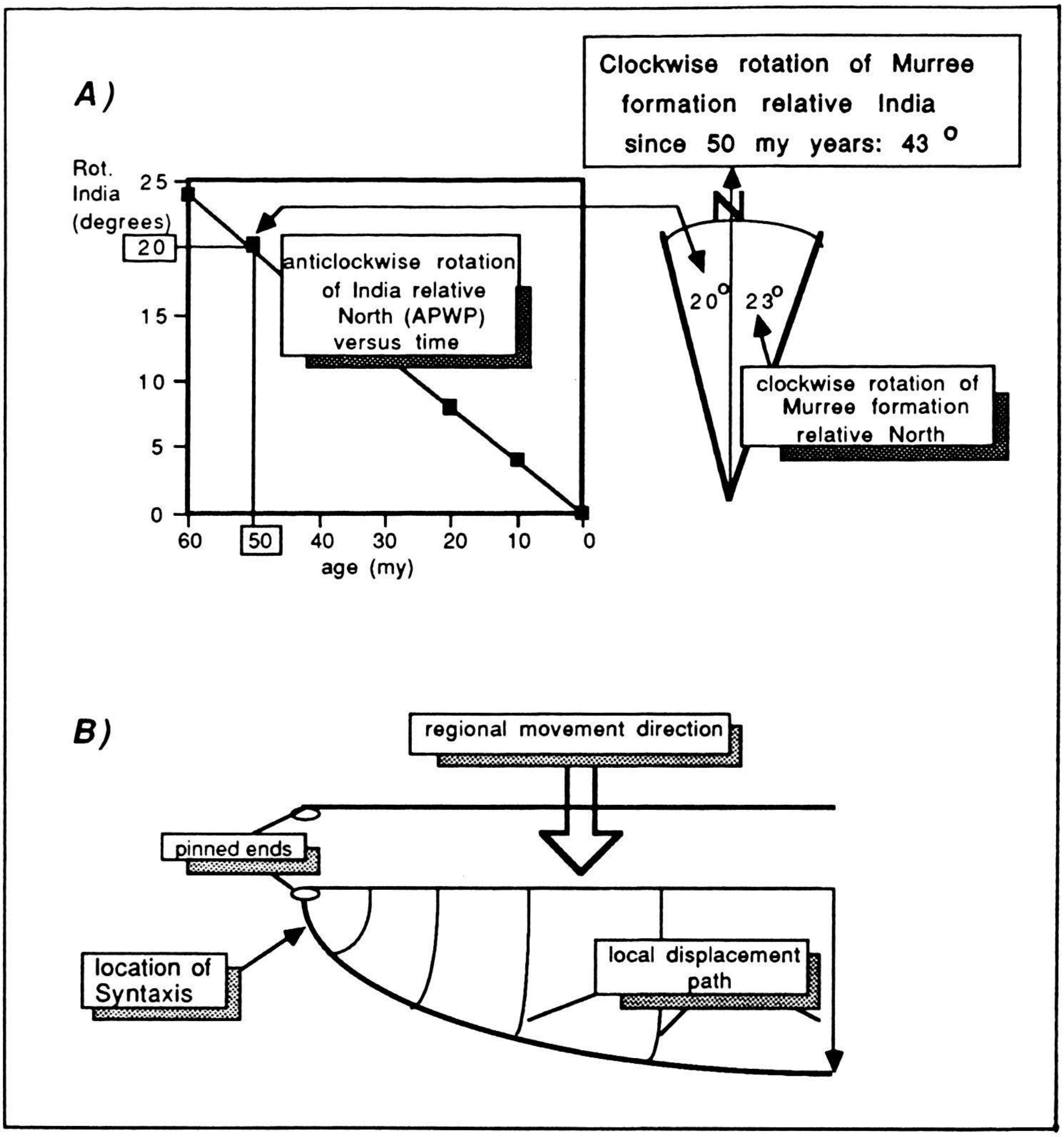



Fig. 4. A) The cover block supporting the sediments of the Murree formation has rotated 43° in a clockwise sense relative to the Indian craton since 50 my.

B) A simple model explaining the clockwise rotation of the Murree formation relative to India: a regional transport direction with a pinned end creates divergent lineation patterns. Transport directions swing clockwise away from their original orientation.

der Path (APWP)-curve has to be added. Using ocean floor magnetic anomalies between India and Madagascar (Powell 1979) and data from several hot spots (e.g. Patriat & Achache (1984), Klootwijk (1985) has constructed a well defined Tertiary APWP-curve for India, which is in agreement with the relative movements of the other Gondwana continents. On this basis, a counterclockwise rotation of 20° of India relative to geographic North since 50 my has been postulated. The clockwise rotation of the Murree beds relative to India is then calculated as 20°+23°=43° (Fig. 4A). This 43° (error in the magnitude of ±10°) of clockwise rotation can explain an aspect of the curvature in the Western Himalayas.

There exist several models to explain the curvature of the Himalayan chains. One regional model (Klootwijk et al. 1985) proposes counterclockwise rotational underthrusting of Greater India and consequent oroclinal bending of the Himalayan chains with back arc spreading on the Tibetan Plateau. Oroclinal bending can also be explained by a simple geometric model (Fig. 4B). Small and large scale structural analysis in the core of the HKS, such as stretching lineations, cleavage pattern and branch lines of thrusts strongly suggests an NE-SW directed mass transport direction. It lies normal to the overall structural trend of the HKS. Similar studies further to the east confirm this divergence of transport directions normal to the Himalayan arc. (e.g. Mattauer 1986). The transport direction to the West of the Syntaxis has been deduced from branch lines near Murree Hill Station as being towards the SSE (Bossart et al. 1988). To the northwest, stretching directions of N 160° into Kohistan are known (Coward 1987). If one assumes a pinned end, then a southward directed regional mouvement swings local transport directions clockwise away from their original north-south orientation. West of the pinned end, the regional movement directions should be parallel to local transport directions.

The simple geometric bending model suggests limited continental underthrusting and little shortening of the hanging wall block in the vicinity of the pinned end. This pinned end is geologically not documented at the surface in the Western Himalayas, but we assume that the apex of the HKS is closer to it than for example localities further to the southwest or southeast. A minimum shortening of 33 km between the Panjal – and Murree thrusts which includes a ductile strain correction in the apex area was obtained (Bossart et al. 1988), whereas in the same zone to the southwest of the Syntaxis, a shortening of about 140 km was calculated by Coward & Butler (1985). The shortening in the HKS apex area is less than that southwest of it, which supports the simple geometric model described above. This simple geometric model requires arc-radial and -parallel extension. There is evidence for some extension along the Himalayan arc. Tapponnier et al. (1981) indicate normal faults oriented radial to the arc. On the other hand the mapping of deformed reduction spots in the Syntaxis never gave an indication of such extensional strains. – A further disadvantage of this model is the mass compatibility: huge block rotations around the pinned end would cause mass incoherency (holes and material accumulation) which is not supported by seismic data (Seeber et al. 1981). Therefore the term block rotation has to be used in a sense that only the cover or part of it has rotated. The deeply buried basement in the HKS probably would indicate different rotation-directions and -amounts.

To prove the consistency of the simple geometric model described above (Fig. 4B), rotation of tectonic blocks relative the Indian craton on a larger scale has to be studied.

| site (Fig. 5) | formation | locality (coordin.) | age (my) | declination (degrees) | inclination (degrees) | k-Fisher | α 95 (degrees) | samples Normal Reverse | Rot. India APWP (degrees) | Rot. rel. India (degrees) | reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | Murree form. | Jhelum valley 73.60E/34.20N | 55-45 | 22.5 | +17.2 | 10 | 9.3 | N 12 R 15 | 20 | 43 clock | this paper |
| B | Basal Murrees | Kalakot inlier ?73.85E/33.34N | ? Early Eocene | 129 | -12.5 | 40 | 3.5 | R 39 | 14-18 | 33-37 anticlock | Klootwijk et al., 1986 a |
| C | Lower upper Murrees | ?74.30E/33.12N | ? Eocene-Oligocene | 204.5 | -23 | 20 | 3.5 | R 91 | 10-14 | 35-39 clock | Klootwijk et al., 1986 a |
| D | Lower Murrees | ?74.30E/33.12N | ? Oligo.-Miocene | 23.5 | +39 | 13 | 4.5 | N 51 R 35 | 8-12 | 22-36 clock | Klootwijk et al., 1986 a |
| E | Lockhart Limest. | Chichali gorge 71.42E/33.00N | 60-65 | 335 | -13 | 11 | 8.5 | N 28 | 24-26 | ±0 | Klootwijk et al., 1986 b |
| F | Hangu form. | Dhak Pass 71.82E/32.70N | 60-65 | 173 | -2.5 | 5 | 14 | N 7 R 19 | 24-26 | 31-33 clock | Klootwijk et al., 1986 b |
| G | Upper Siwaliks | Dhaud Khel 71.65E/32.90N | 2-5 | 356.6 | +35.9 | 42.2 | 8.6 | N 4 R 4 | 1-2 | 1-2 anticlock | Opdyke et al.,1982 |
| H | Lower - middle Siwaliks | Nagri 72.45E/32.75N | 5-12 | 350.9 | +34.8 | 18.4 | 5.3 | N 26 R 16 | 2-5 | 4-7 anticlock | Opdyke et al.,1982 |
| I | Lower - middle Siwaliks | Chakwal Bhaun 72.75E/32.85N | 5-12 | 330.7 | +31.8 | 13.1 | 6.4 | N 25 R 16 | 2-5 | 24-27 anticlock | Opdyke et al.,1982 |
| J | Lower - middle Siwaliks | Dhala Nala 73.20E/32.85N | 5-12 | 328.5 | +35.9 | 37.6 | 5.5 | N 14 R 5 | 2-5 | 26-29 anticlock | Opdyke et al.,1982 |
| K | Upper Siwaliks | Kotal Kund 73.30E/32.75N | 2-5 | 320.8 | +34.1 | 15.6 | 4.6 | N 37 R 29 | 1-2 | 37-38 anticlock | Opdyke et al.,1982 |
| L | Upper Siwaliks | Chambal Ridge 73.45E/32.70N | 2 | 351.7 | +37.4 | 17.8 | 3.7 | N 49 R 38 | 1 | 7 anticlock | Opdyke et al.,1982 |
| M | Upper Siwaliks | Tatrot 73.35E/32.85N | 2-5 | 327.7 | +36.7 | 17.3 | 3.9 | N 45 R 36 | 1-2 | 30-31 anticlock | Opdyke et al.,1982 |
| N | Lower - middle Siwaliks | Bora Kas 72.61E/33.23N | 7-12.5 | 350.3 | +36.3 | 9.7 | 7.1 | N 30 R 15 | 3-5 | 5-7 anticlock | Tauxe at al., 1982 |
| O | Middle Siwaliks | Malawalla Kas 72.64E/33.25N | 7-8.5 | 353.7 | +35.5 | 8.0 | 9.1 | N 21 R 14 | 3 | 3 anticlock | Tauxe at al., 1982 |
| P | "Foredeep Sediments" | Soan Syncline 73.10E/33.40N | 9 | 317 | — | — | — | — | 4 | 39 anticlock | Burbank, 1984 |
| Q | "Peshawar basin sediments" | Dag, Garhi Chanda 73.10E/33.40N | 2.5 | 358 | — | — | — | — | 1 | 0-1 clock, anti. | Burbank, 1985 |

Table 1
Primary magnetic remanence directions and relative rotations of Tertiary formations, Northern Pakistan.

Therefore the available data of Tertiary NRM measurements beyond the Main Boundary thrust in Northern Pakistan and Indian Kashmir were compiled and listed in Table 1. The rotation amount of the different lithological units relative to the Indian craton is shown in Fig. 5. Three main features can be seen:

1. The magnetic vectors in Fig. 5 are defined as relative rotations of blocks supporting Tertiary lithological units relative to the Indian craton. Geographic north serves as reference line. In general these magnetic vectors trend to lie normal to the structural trend (folds, thrust).

2. In the core of the Syntaxis and southeast of it (localities A, C and D, Fig. 5), a *clockwise* rotation of the Murree formation relative to the Indian craton of about 45° is observed. Locality B as an exception is explained by a local structural "disturbance" (Klootwijk 1986b) and can therefore be neclected from a regional interpretation. In the west of the Syntaxis, partly *no* rotation and partly a clear trend to *counterclockwise* rotation near the Syntaxis is recorded. The amount of rotation in general is less than 30°.

3. Two different transport directions around the Syntaxis were mapped. The eastern and early one is parallel to the clockwise rotated magnetic vector in the Syntaxis

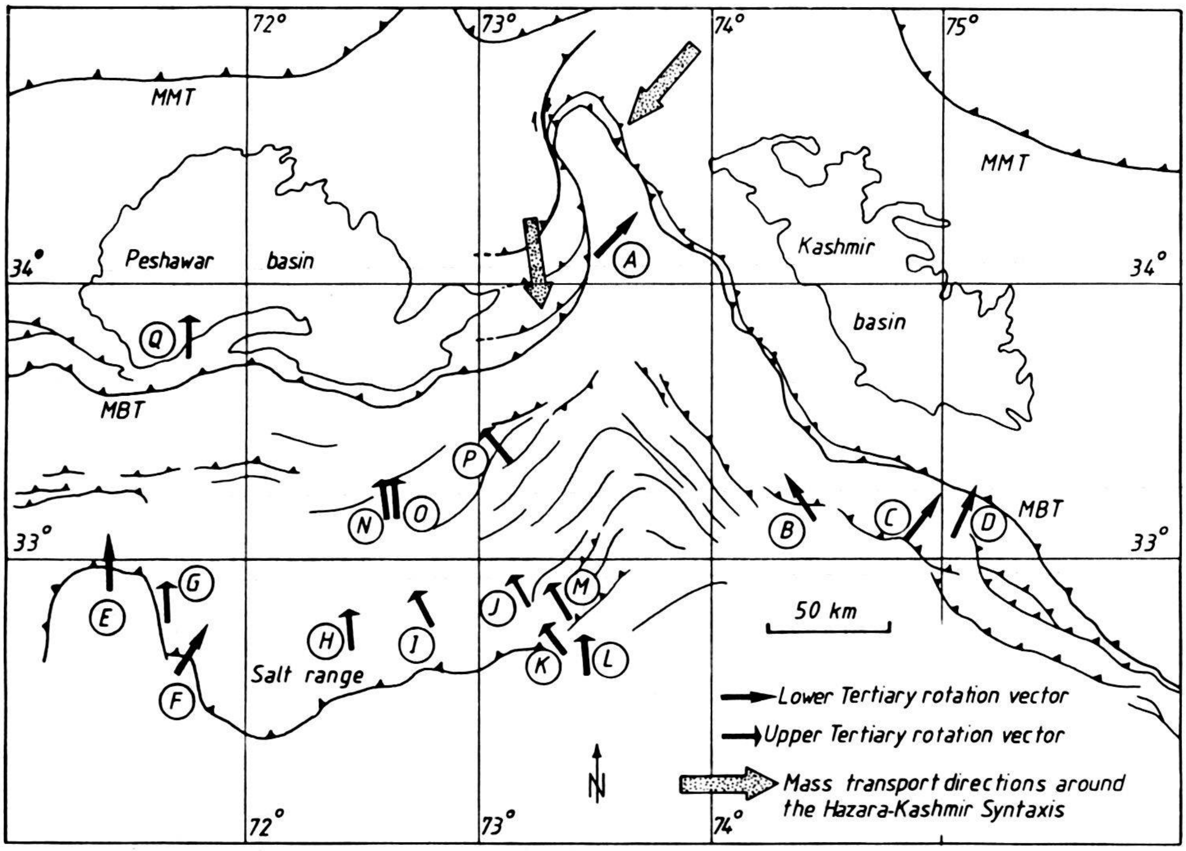



Fig. 5. Different paleomagnetic sampling localities (A–P, Table 1) with known rotations relative to the Indian craton below the Main Boundary thrust (locality Q is above the MBT). Locality A lies in the Jhelum valley and is the result of the present investigation. Mainly involved are sediments of the early- (60–40 my, long arrows) and late (<15 my "Siwaliks", short arrows) foreland basin in Northern Pakistan and Indian Kashmir. MMT = Main Mantle thrust.

and the western and later one tends to be parallel to the slightly counterclockwise rotated magnetic vectors on the Potwar Plateau and the Salt range region.

In the light of these observations, two questions arise with regard of the formation of the Syntaxis:

– Is there a visible surface expression of the transition "large clockwise rotations in the Syntaxis" and "slight counterclockwise rotation" in the west?

– What is the geological reason of these rotational changes?

We propose that the border of clockwise and counterclockwise rotations lies close and parallel to the strike trend of the Muzaffarabad anticline, merging into the mylonite zone of the Balakot shear zone at the western side of the Syntaxis (Fig. 1). The Muzaffarabad anticline probably masks a major blind thrust in the footwall block of the Murree formation, that is documented further to the southeast, in Indian Kashmir, where the Murree formation is thrust over Siwalik molasse deposits. The Balakot shear zone cuts the NW-SE directed structural trend of the Syntaxis. Furthermore it marks the transition zone of the early SW to the late SSE transport directions. This discontinuity is therefore the most obvious geological argument for the rotational changes of the magnetic vectors. To the north, the border of rotational changes is not clear: the increase in deformation and in metamorphism distorts the information contained in the primary remanence directions.

The geological reason why the "block rotations" change to the west of the Hazara-Kashmir Syntaxis might be explained by the "salt-no salt" model of SEEBER & ARMBRUSTER (1981). In the Syntaxis and east of it, there is a strong coupling of Indian basement and cover, whereas to the southwest of it the widespread and often thick Cambrian evaporite deposits act as ideal décollement horizons between basement and cover (Salt range). Large clockwise rotations, basement thrusting and thrusting at the surface occur simultaneously where evaporites are absent. There is little or no rotation where thrusting occurs in the salt.

Slightly counterclockwise rotation in the Salt range and Potwar Plateau has occurred at different times in response to segmentation of the hanging wall thrust sheet (OPDYKE et al. 1982). Cross section balancing does not support a regional counterclockwise rotation of the Salt range hanging wall block (LILLIE et al. 1987, BAKER et al. 1988); these paleomagnetic counterclockwise rotations in the southwest of the HKS represent only local rotations of thrust sheets around nearby poles. – Large clockwise rotations in the HKS and southeast of it belong to a large regional rotation system rather than to local rotations of thrust sheets. KLOOTWIJK et al. (1985) suggest, that the rotation centre of this system lies about 70 km northwest of the HKS, at the intersection of the Indus Kohistan Seismic Zone and the Main Mantle thrust.

### *2.4 A magneto-structural model for the formation of the Syntaxis* (Fig. 6)

The palaeomagnetic studies require a large clockwise rotation of the thrust sheets relative to the Indian craton in and east of the HKS, whereas west of it there is in general no or small counterclockwise rotation of thrust sheets relative to the craton. From the mapping of the structures, the formation of the HKS can best be interpreted by a counterclockwise rotation of transport directions from 220° to 160°, where the reference frame is geographic north. A differentiated interpretation of the HKS can be achieved by a combination of both the regional and the local model: the early transport direction (Fig. 6C: from 1. to 2.) was initially reversed to the mean movement vector of India and was then successively rotated clockwise to its 220° position. The late transport direction (Fig. 6C: from 2. to 3.) in the west was slightly rotated counterclockwise to its 160° position together with the slight counterclockwise rotation of the Indian craton. It essentially never changed its orientation and was always more or less reversed to the mean Indian movement.

This model combination relates the complicated orientation pattern of transport directions around the HKS with the simple regional convergence directions (the mean indentation directions of India into Asia). As far as our structural model based on field mapping is concerned, we have to assume passive clockwise rotation of linear and planar deformation fabrics, e.g. stretching lineations and cleavage planes, although there is no direct field evidence for such rotations.

### *2.5 The paleomagnetic sections in the Neelum – and Kaghan valleys*

Directions of characteristic remanence magnetizations (ChRM) in the Neelum- and Kaghan sections, non-dip corrected and dip corrected, are shown in Fig. 3. Their directional pattern (declination and inclination values) show a larger scatter and different orientations in comparison with those found in the Jhelum valley.

In the Neelum valley it is shown that the formation of the cleavage is responsible for the deviation of the magnetic vectors: from W to E the magnetic vectors have a tendency to rotate passively towards the cleavage plane (Bossart et al. submitted to *Tectonics*). Instead of the conventional bedding tilt correction, we have corrected the non-dip corrected remanent directions in the Kaghan valley by an inverse rotation of the material buckling (domal fold) deduced by fibrous vein systems. This inverse rotation was done in the XY- and XZ-principal planes resulting in a northwest-southeast striking girdle of remanent directions (Fig. 3, stereogram on the top, right hand side). This girdle is parallel to the overall strike trend of the slaty cleavage in the Kaghan valley (see also cleavage strike trend Fig. 1). In fact the inverse material rotation has not produced the same direction pattern as in our reference profile in the Jhelum valley.

Independently the AMS data confirm this distorsion of NRM directions in the Neelum- and Kaghan sections (Bossart et al. submitted to *Tectonics*): the superposition of various tectonic strains (cleavage, mylonite shear zone, refolded folds) in the Neelum- and Kaghan sections leads to orientations and shapes of AMS ellipsoids which can be correlated with the ellipsoidal forms of deformed reduction spots. This progressive deformation from south to north, which is derived by deformed reduction spots and the magnetic fabric, is responsible for the distortion of the primary NRM directions. It seems improbable that an inverse strain correction of the ChRM directions in the Neelum- and Kaghan sections results in similar primary NRM directions as obtained in the Jhelum section.

## 3. Conclusions

1) In the three sections characteristic remanence directions were obtained by thermal cleaning for a large proportion of the samples collected. The main carrier of mag-

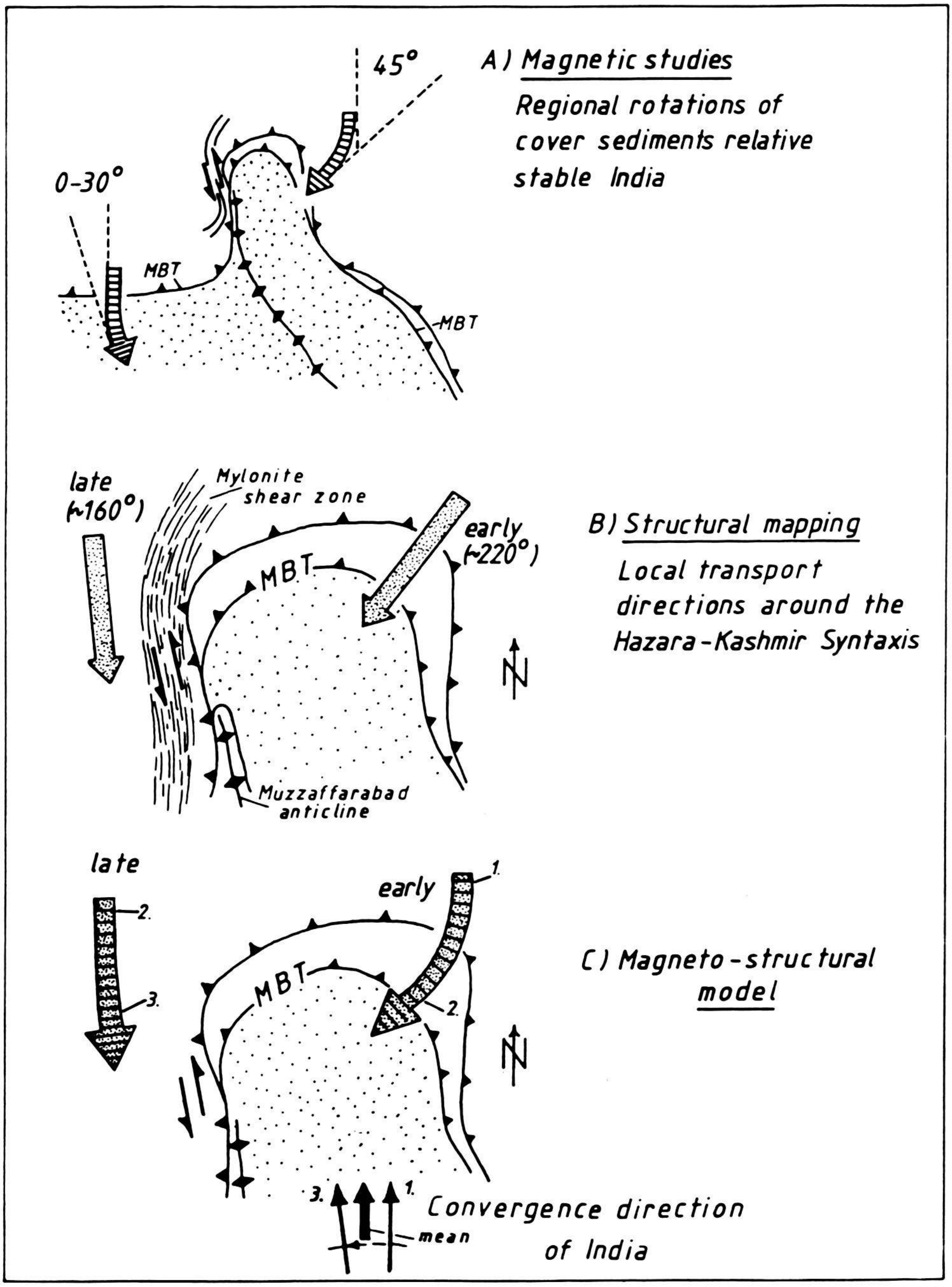



Fig. 6. A magneto-structural model for the formation of the Hazara-Kashmir Syntaxis. The combination of both the regional (A) and the local (B) model results in an early transport direction, which was initially inversed to the mean movement vector of Indian and was then successively rotated to its 220° position (C). The late transport direction in the west never changed its orientation and was always more or less inversed to the mean movement vector of India.

netization resides in haematite with high unblocking temperatures. Polarity changes in the very little deformed Jhelum section give evidence for an early if not primary magnetization origin. The NRM intensities do not vary significantly in all the sections.

2) The oldest Murree beds in the HKS are of Late Paleocene age (55 my). There are no older molassic deposits reported in the Subhimalaya of northern Pakistan. These molassic red beds are indicative of the formation of the early foreland basin related to lithospheric loading during the suturing process of the northwestern Indian margin and the island arcs. The mean dip corrected inclination values of the Jhelum section demonstrate the development of this early foreland basin at about 8° N. In comparison with the actual latitude of the Murree beds in the Syntaxis, this foreland basin has been displaced together with the Indian craton at least 2600 km to the north (minimum value because of the allochthonous nature of the actual HKS).

3) The structural remapping of the HKS leads to the conclusion, that counterclockwise rotation of the overthrust shear direction from an early NE-SW direction (220°) to a later NNW-SSE direction (160°) is responsible for the formation of the Syntaxis. On the other hand the paleomagnetic data suggest a large clockwise rotation relative to India of about 45° in and east of the HKS. The combination of these two motions leads to a different magneto-structural model for the formation of the HKS: the early transport direction was initially reversed to the generally northward directed movement vector of India and was then passively rotated in a clockwise sense to its present 220° directed position. The late transport direction which is observed in the southwest of the HKS, was always roughly antiparallel to the mean Indian movement vector. Slightly counterclockwise rotation relative to India to achieve its 160° direction is suggested by Tertiary paleomagnetic data in the Salt range and the Potwar Plateau.

4) The structural remapping of the HKS shows an increase of deformation from the Jhelum section in the south to the Neelum- and Kaghan sections in the north, where finite strains reach maximum values. In the Neelum- and Kaghan sections a passive rotation of the ChRM directions towards the cleavage plane is seen. There is no alignment of ChRM directions parallel to the maximum extension direction in the two northern sections, as the random orientation of ChRM directions within the cleavage planes show. The Neelum- and Kaghan sections are not suitable for a regional paleomagnetic interpretation.

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